# 5. Synthesis of Human Response in Closed-Loop Tracking Tasks

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Previous investigations have determined linear, average constant-coefficient models that provided a reasonable reproduction of a human controller's response in tracking tasks. However, when such models are put in a control loop in place of a human, they do not exactly reproduce the system response obtained with the human controller. These previous studies suggest that time variations of the model coefficients and a random noise signal should be added to the linear model to obtain a more accurate representation of the human's response.

In this present study, experiments have been conducted to determine the variability in a human subject's control stick response to displayed displacement and rate of change of displacement to aid in the implementation of the time variations to be included in the model. Also, additional tracking tasks were made to obtain a definition of the characteristics of the random noise to be added to the model. These two factors were then added to the model, and this composite model was placed in a control loop in place of the pilot. The results demonstrate that this composite model reproduces time-history characteristics and mean-square system errors that more closely match the human subject than does the linear model.

## INTRODUCTION

While linear models of pilots have proven to be very useful in the analysis of manually controlled systems (for example, as shown in references 1 and 2), these linear models lack the random nature of human subjects and, therefore, have lacked complete accuracy. Taking the average gains as measured by parameter tracking methods, constructing a model with these gains, and placing this model in a control loop in place of the pilot results in a lower mean-square system error than obtained with the human subject. This fact is demonstrated in reference 3 where the task involved the compensatory control of a random signal. The experiments described in this paper test the hypothesis that adding a random noise signal and the time varying gains to the linear model will provide a greatly improved match of the system error to that error obtained with a human subject.

The fact that the human controller is not strictly linear is illustrated in figure 1. The figure presents time histories obtained during tests of compensatory tracking with acceleration dynamics in which the forcing function was a pure sine wave. If the subject did respond in a linear manner the system error would be a sine wave, which, after the initial transient had died out, would be of the same frequency as the disturbance function. However, the figure clearly indicates that this is not the case. These results, and similar results presented in reference 4 where the controlled dynamics were a simple amplifier, suggest that the human controller is a noise source, and therefore his output contains a random signal. In addition to the evidence of a noisy control signal given in the figure, there is also evidence of time varying linear system characteristics. Short sections of very uniform exponential divergences, such as would be produced by an unstable or poorly damped linear system, can be seen. These divergences indicate that the human should also be considered as being a time varying controller. These two factors, the random output and the time variation, were considered as being the factors that should be added to the linear model to provide an improvement in the representation of the human subject.

## TIME VARIATIONS

To determine just how much time variation and how much random signal to add to the linear model, some special tests were made. To determine the magnitude of the time variation that should be used, the static response in stick position to displayed signals was determined. In these tests the subject observed a large oscilloscope display on which, in the first series, a horizontal line moved from top to bottom or bottom to top at fixed rates. These rates were from 0 to ±80 cm/sec, or, in terms of line-of-sight rotation, from

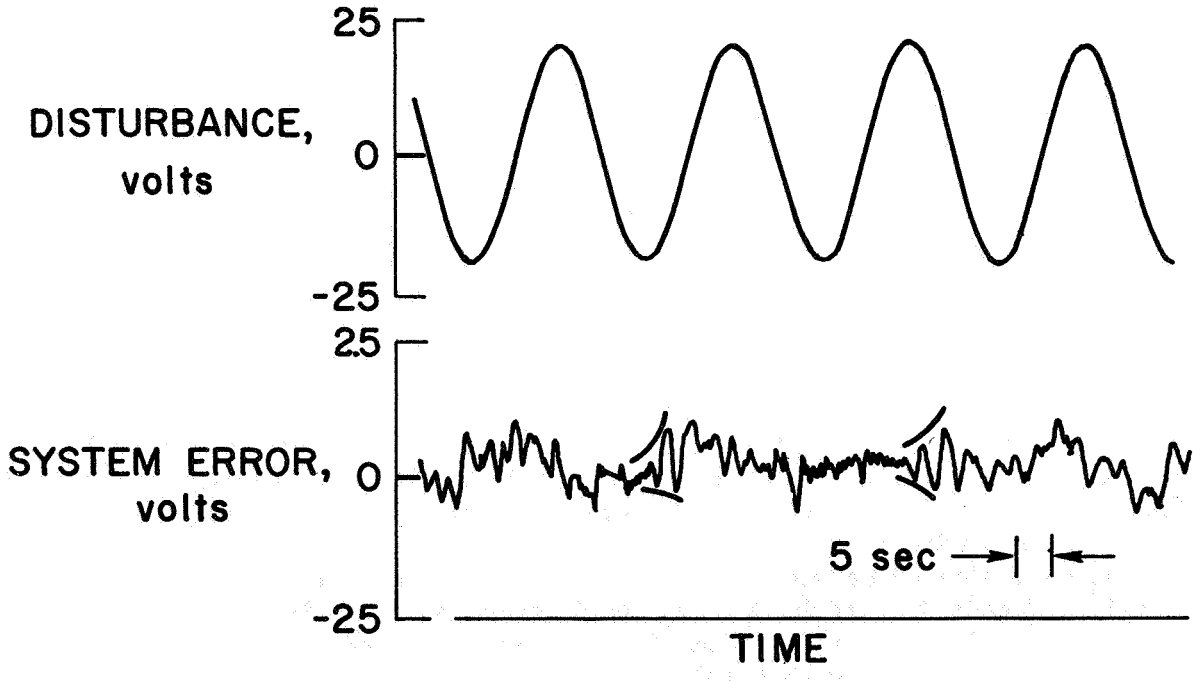


Figure 1.—Closed-loop response to a sine wave disturbance.

0 to ±1.1 rad/sec. The subject responded by moving a side-arm controller to a position that he felt was an appropriate response and held this response long enough to establish a fixed value. These were open-loop tests. The controller deflection did not influence the display. The subjects were not instructed to establish any particular gain for these responses, but only to be consistent.

Typical results of these tests are shown in figure 2. The first thing that can be deduced from this plot is that the response is linear. A straight-line average fit to this data can be drawn which defines the subject's gain. Also, straight-line boundaries for the data scatter can be drawn, establishing the subject's spread in his gain. The percentage of this spread from the average gain for each of the subjects is shown in the figure. It can be seen that this spread averages ±45 percent for all of the subjects. This ±45 percent was used as the amplitude of time variation of the lead gain for the linear model. The average gain was taken as that value established by the parameter tracking method, and this average value was perturbated ±45 percent.

Similar tests were performed to establish the spread in response to display displacement. The spread in the use of displacement was found to be ±30 percent, and this ±30 percent was applied to the static gain of the linear model.

The time characteristic of the gain variations was implemented as follows. Records such as that presented in figure 1 show that manually controlled systems are poorly controlled for periods of 5 seconds. To duplicate this condition the variable gains were given a saw tooth variation that had a cyclic period of 20 seconds. The static and lead gains were varied together - both high and both low at the same time. Thus the model controlled system operated at nominal gains for 10 seconds during every cycle, and low and high gains for 5 seconds.

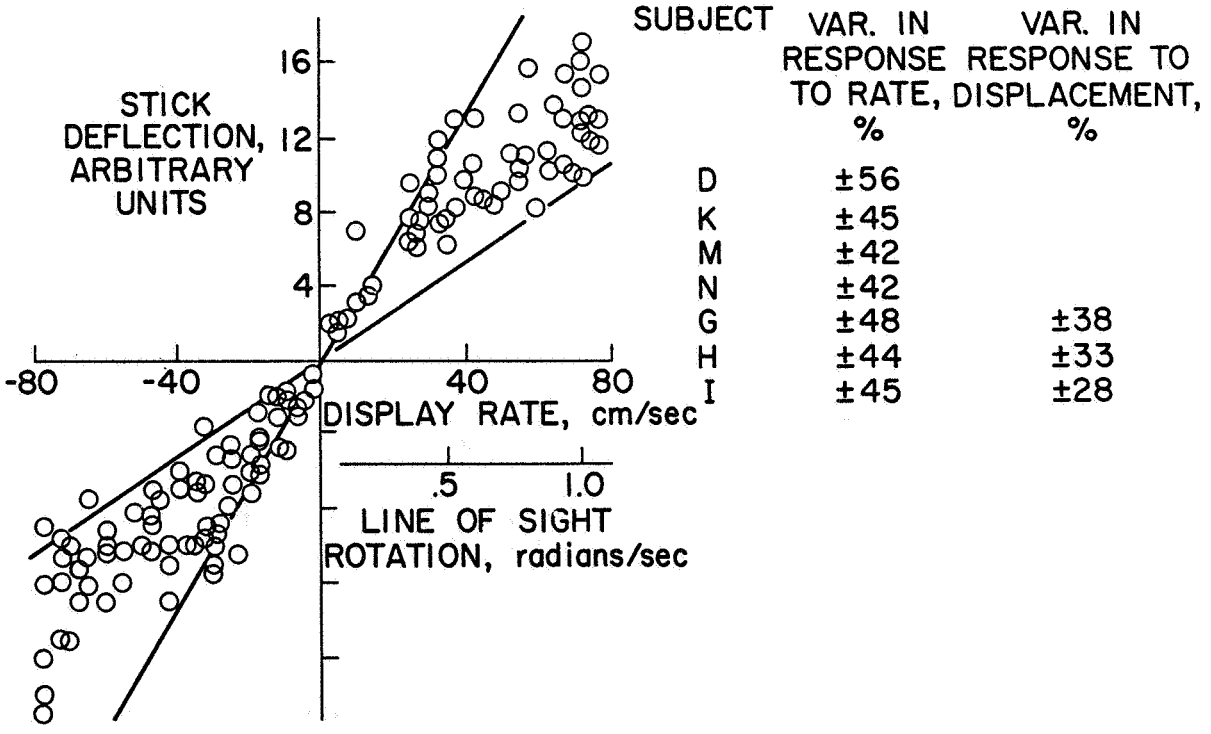


Figure 2.—Static stick response to displayed signals.

## RANDOM SIGNAL

The amplitude and spectral density of the pilot-injected noise were obtained from data gathered during compensatory tracking tests. In these tests the subjects controlled acceleration dynamics and the disturbance function was adjusted to have different mean-square value from run to run. The pilot-injected noise was taken to be the difference between the pilot's output and the output of the adjustable model used in the parameter tracking method as described in reference 5.

The variance of the various signals around the control loop for one subject is shown in table 1.

TABLE 1.—VARIANCES AND RATIOS

| Variance | | | | Ratios | |
|---|---|---|---|---|---|
| Disturbance, volts$^2$ | System error, volts$^2$ | Stick, volts$^2$ | Pilot noise, volts$^2$ | $\frac{\text{Error}}{\text{Disturbance}}$ | $\frac{\text{Pilot noise}}{\text{Stick}}$ |
| 5.61 | 3.57 | 0.775 | 0.356 | 0.64 | 0.46 |
| 15.4 | 16.2 | 1.81 | .535 | 1.05 | .30 |
| 53.1 | 35.7 | 11.0 | 3.36 | .67 | .31 |

Although there were variations between subjects, the values shown are typical. It can be seen that all of these values increase as the variance of the disturbance function increases. To determine a generalized nondimensional number, the ratio of the variance of the measured pilot noise to stick deflection was formed. This ratio was the most nearly constant of all the ratios that could be formed. The average value for the subject whose data are shown in table 1 is 0.36. For all the pilot subjects the values of ratio of pilot noise to stick deflection ranged from 0.20 up to 0.47.

The spectral density of the pilot noise is shown in figure 3. Also presented is the square of the input-output ratio of two first-order lags with break frequencies of 10 rad/sec. The good agreement between these two curves is clearly seen. For all the subjects the shape of the spectral density of the pilot noise had the characteristic of a second-order system with a break frequency that varied from 10 to 15 rad/sec. To simulate this pilot noise, the output of a noise generator was passed through two first-order filters with break frequencies of 10 rad/sec. The amplitude of the noise was adjusted until the ratio of stick deflection to noise was the proper value. This adjustment was done while the model was in the control loop. Since the model was in the control loop, adding noise to the output of the model changed the stick deflection in a manner that could not be accurately predicted. Therefore, the adjustment to the amplitude of the noise had to be adjusted in an iterative manner. It was possible after one iteration to arrive at approximately the desired amplitude for the added noise.

## SYNTHESIS OF HUMAN RESPONSE

The simulated pilot noise and the time varying gains were added to the pilot model in a manner illustrated by the block diagram shown in figure 4. The ±30-percent variation on the static gain was placed at the output of the model. The ±45-percent total variation on the lead

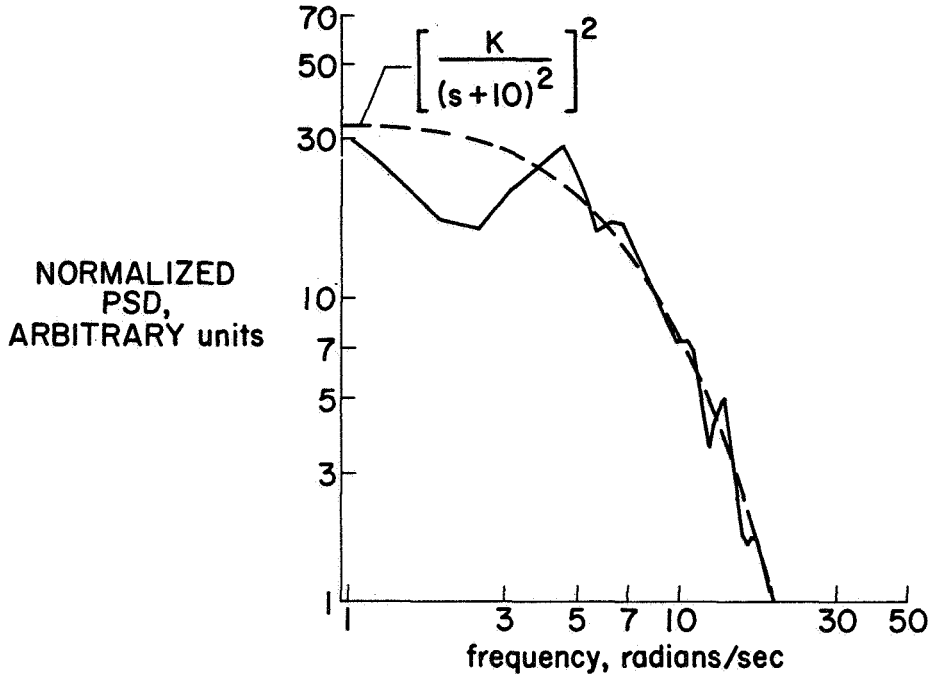


Figure 3.—Power spectral density of pilot noise.

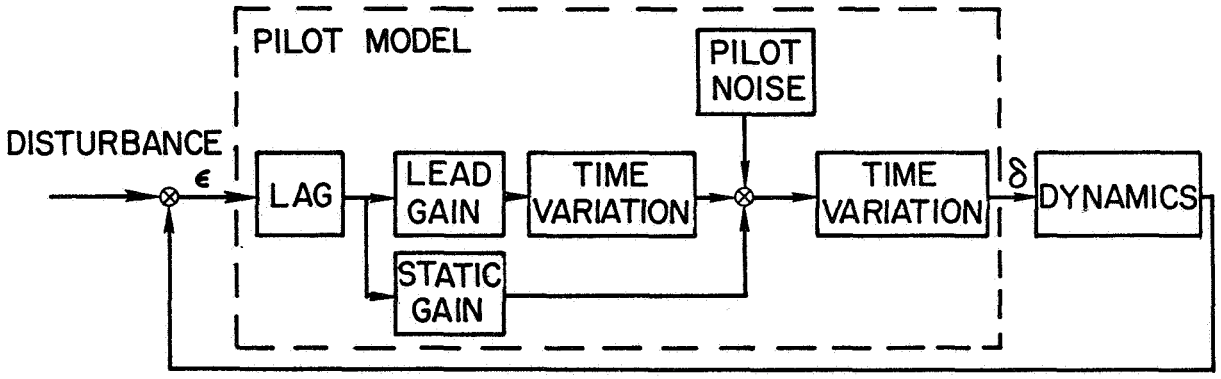


Figure 4.—Block diagram of closed-loop system with composite model.

gain was achieved by putting an additional ±15-percent variation on the lead gain. The pilot noise was inserted in the model ahead of the output of the model. With this arrangement the ratio between noise and stick deflection would remain constant even though the static gain was being varied.

The results obtained with this composite model are presented in figure 5. Presented are the system errors obtained with the human controller in the loop, with the composite model in the loop, and with the linear model in the loop. The same disturbance function was used in obtaining each of these three records. It can be seen that the composite model provides a great improvement in the match of the time-history characteristics of the system error over that obtained with the linear model. The ratios of the mean-square values of the

system error to disturbance are also presented to further illustrate the improvement in the match. For this particular example the ratios are as listed in table 2.

The human pilot did not perform with the same ratio of mean-square system error to disturbance for each of the 3-minute tests that he made, as illustrated in table 1. Neither did the composite model. To illustrate that the spread in performance with the composite model was the same as that obtained with the human pilot, table 3 is presented. The figure shows the average of the ratio of mean-square system error to disturbance and the variation for the

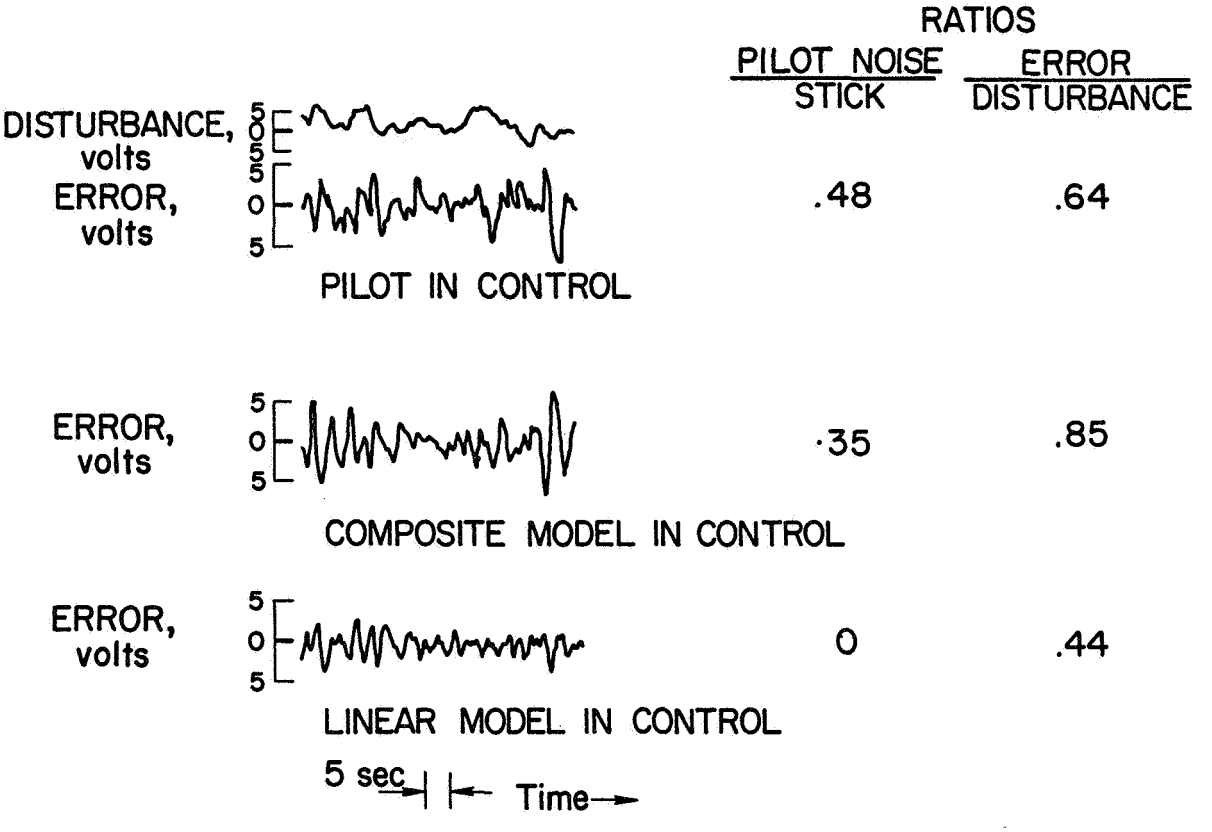


Figure 5.—Comparison of system response with pilot, composite model, and linear model in control.

TABLE 2.—DATA FOR FIGURE 5

| | $\frac{\text{Noise}}{\text{Stick}}, \frac{n^2}{\delta^2}$ | $\frac{\text{Error}}{\text{Disturbance}}, \frac{e^2}{D^2}$ |
|---|---|---|
| Pilot | 0.48 | 0.64 |
| Composite model | .35 | .85 |
| Linear model | 0 | .44 |

three tests performed by the pilot, for six tests performed with the composite model, and for five tests performed with the linear model. Here again it can be seen that an improvement in the match to the human pilot is obtained with the composite model over that obtained with the linear model.

The largest part of the improvement achieved with the linear model was provided by the addition of the random noise. Table 4 illustrates this fact. It can be seen that nearly four-fifths of the improvement is provided by the addition of the noise.

TABLE 3.—AVERAGE DATA

| | $\frac{\text{Error}}{\text{Disturbance}}, \frac{e^2}{D^2}$ |
|---|---|
| Pilot | 0.78; +0.26, -0.12 |
| Composite model | .73; +.37, -.19 |
| Linear model | .35; +.08, -.05 |

TABLE 4.—AVERAGE DATA

| | $\frac{\text{Error}}{\text{Disturbance}}, \frac{e^2}{D^2}$ |
|---|---|
| Pilot | 0.78 |
| Composite model | .73 |
| Linear model with added noise only | .70 |
| Linear model with variable gains only | .43 |
| Linear model | .35 |

## CONCLUSIONS

The data presented in this paper demonstrate that human pilot response can be more closely matched by a linear model to which have been added time variations in the gains and a random signal than with the linear model alone. In the case of multiaxes tasks and in cases where side tasks must be performed in addition to the closed-loop control, references 6 and 7 have prescribed additional changes that should be included in the model. These additions involve the reduction of certain gains to zero for prescribed lengths of time. Other changes in the gains of the linear portion of the model that correspond to various vehicle dynamics are presented in references 3, 8, and 9. By following the suggestions for the synthesis of pilot response presented in this paper and in the references, pilot models for a large portion of all probable control situations can be constructed. The simple, linear, constant-coefficient models can be used to predict, or confirm, gross system performance. For detailed studies of precision of control, structural loads, and fuel requirements the composite model should be used.

## REFERENCES


1. Ashkenas, Irving L.; Jex, Henry R.; and McRuer, Duane T.: Pilot-Induced Oscillations: Their Cause and Analysis. Norair Rept. NOR-64-143 (Rept. STI TR-239-2), Northrop Corp., June 20, 1964.
2. Adams, James J.: Application of Human Transfer Functions to a Design Problem. Third Annual NASA-University Conference on Manual Control, NASA SP-144.
3. Adams, James J.; and Bergeron, Hugh P.: Measurements of Human Transfer Functions With Various Model Forms. NASA TN D-2394, 1964.
4. Pew, R. W.: Sine Wave Tracking Revisited. Second Annual NASA-University Conference on Manual Control, NASA SP-128.
5. Adams, James J.; and Bergeron, Hugh P.: Measured Variations in the Transfer Function of a Human Pilot in Single-Axis Tasks. NASA TN D-1952, 1963.
6. Adams, James J.; Bergeron, Hugh P.; and Hurt, George J., Jr.: Human Transfer Functions in Multi-Axis and Multi-Loop Control Systems. NASA TN D-3305, 1966.
7. Bergeron, Hugh P.; Adams, James J.; and Hurt, George J., Jr.: The Analysis of Human Response in Combined Control Tasks. NASA TN D-4356, 1968.
8. Bergeron, Hugh P.; Kincaid, Joseph K.; and Adams, James J.: Measured Human Transfer Functions in Simulated Single-Degree-of-Freedom Nonlinear Control Systems. NASA TN D-2596, 1965.
9. Adams, James J.; Kincaid, Joseph K.; and Bergeron, Hugh P.: Determination of Critical Tracking Tasks for a Human Pilot. NASA TN D-3242, 1966.